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HIGH-STRENGTH COPPER-BASE ALLOYS FOR SHIPBOARD SYSTEMS: Mn-Ni-Al BRONZE: PROGRESS REPORT NO. MAB-1, UP TO MARCH 1, 1983.

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METALLURGY SECTION

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PHYSICAL METALLURGY RESEARCH LABORATORIES
REPORT: MRP/PMRL 82-47(TR)

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HIGH-STRENGTH COPPER-BASE ALLOYS FOR SHIPBOARD SYSTEMS: Mn-Ni-Al BRONZE: PROGRESS REPORT NO. MAB-1, UP TO MARCH 1, 1983

by

A. Couture and M. Sahoo

ABSTRACT

Large manganese-nickel-aluminum bronze (MAB) propeller blades have a higher failure incidence than those made of nickel-aluminum bronze (NAB). Although the mechanical properties of test coupons cut from failed ice breaker propellers appear "normal" in all other respects, impact resistance is abnormally low.

The main purpose of the present work is to determine the reason for the low impact resistance of heavy section MAB castings and to find ways of improving it. In the course of this work, the effect of Mn and Al contents will be studied. To this end, large blocks and continuously cast rods and bars were produced for use in future tests. Their "as cast" mechanical properties and microstructures have been determined and are reported.

LABORATOIRES DE RECHERCHE EN MÉTALLURGIE PHYSIQUE
RAPPORT MRP/PMRL 82-47(TR)

LES ALLIAGES À BASE DE CUIVRE À HAUTE RÉSISTANCE POUR LES BORDS DE NAVIRES ET LE BRONZE Mn-Ni-Al: RAPPORT D'ACTIVITÉ NO MAB-1, JUSQU'AU 1er MARS 1983

par

A. Couture et M. Sahoo

RÉSUMÉ

On rencontre plus souvent des défauts dans les grandes ailes des hélices en bronze conçues à base d'alliages de manganèse-nickel-aluminium (MAB) que dans celles en bronze au nickel-aluminium (NAB). Bien que les propriétés mécaniques des échantillons prélevés des hélices défectueuses de brise-glaces semblent "normales" sous tous les autres aspects, celui de la résistance à l'impact est anormalement faible.

Le but principal des présents travaux consiste à déterminer la raison de la faible résistance à l'impact des sections lourdes des pièces coulées en MAB, et de trouver des façons de les améliorer. Au cours de ces travaux, on étudiera les effets des contenus de Mn et Al. A cet effet et en vue d'essais prochains, on a produit de grands blocs, ainsi que des tiges et des barres coulées en continu. On a déterminé et rapporté leurs propriétés mécaniques "de coulée" ainsi que leurs microstructures.

BACKGROUND

High manganese-nickel-aluminum bronzes (MAB) were used for many years to make large marine propellers and apparently behaved satisfactorily in service.

These MAB alloys were developed in the late 40's and early 50's by Stone and Co. of England and were known by the trade names of Novoston, Superston 40 and Superston 70 according to their manganese content. Development of the alloys was reported by Langham and Webb (1). Chemical compositions, covered by ASTM/ANSI designation B148-78 (alloy C95700) and by British Standards 1400:1973 (alloy CMA1), are given in Table 1 and the mechanical properties, characterized as typical in Stone's literature (2,3), are given in Table 2 together with specification minima.

A number of failures of MAB propeller blades have been reported in recent years both in the USA and in Canada (4-10). Statistical data provided by the American Bureau of Shipping (4) show a total of twenty three fatigue failures of aluminum-bronze propellers over a 10-year period. Four of the twenty three were made of ordinary nickel-aluminum bronze (NAB) and nineteen were made of MAB bronzes; however, no mention is made of the number of propellers of either alloy in service. However, Lloyd's statistics (4) on propeller blade failures at the blade root, in ships built between 1960 and 1971, are more revealing, as shown below:

Lloyd's statistics on propeller failures at the blade root in ships built between 1960 and 1971* (as related to composition).

Propeller material	A	B	C	D
Manganese-aluminum bronze (ABS type 5)	23	240	1200	1.92
Nickel-aluminum bronze (ABS type 4)	3	500	2364	0.13

*A = number of propellers affected; B = number of propellers at risk; C = aggregate years of service of propellers at risk; D = incidence of failure in 100 years' service.

This table indicates that 23 MAB propellers out of 240 at risk, failed, compared with only 3 out of 500 NAB propellers. Thus, 10% of the MAB propellers were adversely affected compared with only 0.6% of the NAB propellers. When

the failure incidence for 100 years of service is considered, it is seen to be 15 times higher for MAB propellers than for NAB propellers - a significant difference.

Raymond (5,6) obtained the results given in the second column of Table 3 from test coupons cut from the remains of two blades of MAB propellers failed in service. Included in the same table are the results of investigations carried out by Edwards and Couture of the Physical Metallurgy Research Laboratories (PMRL) of CANMET, Department of Energy, Mines and Resources, on blades from failed MAB propellers from the CCGS John A. MacDonald and the CCGS Franklin (7,8,9). Tests were done on specimens from one failed and two "good" blades from the CCGS John A. MacDonald the tips of the other two (undamaged) blades of one propeller were cut to compensate for the loss of portions of two blades to enable the ship to continue on her way. Specimens were also obtained from failed blades #1 and #3 from the CCGS Franklin. The values which appear in the last column of Table 3 are 75% of the strength values specified for separately cast test bars. A 75% benchmark was suggested by Langham and Webb (1) who obtained strength values 75-80% of those of separately cast test bars at the roots of the blades of a 5000 kg propeller. The benchmark was also acknowledged by Tuffrey in his discussion of Raymond's paper (6). The dimensions shown at the top of "PMRL" columns (Table 3) indicate the approximate blade thickness at the site where the test coupons were cut.

Table 3 indicates that the blades tested by Raymond have lower strength, elongation and hardness values than those tested at PMRL, although Charpy V-notch (CVN) impact properties are identical; the only exception is blade "B" whose impact resistance is higher than that of the other blades, although it is still too low. It is also apparent that there is no relationship between strength, elongation and hardness on one hand and impact resistance on the other. The strength values of the blades are generally well above those required in large castings even when the 75% factor is applied to the so called "typical" strength values of separately cast test bars. However, the impact resistance of the blade material is only 25% of "typical" values.

Because ice breakers frequently encounter ice conditions far more severe that those for which they were originally designed, the propellers must sometimes be used to free the ship so that she can proceed. However, in practice, this could lead to brittle fracture of propeller blades, particularly if - as seems to be the case - the material has a low impact resistance (5-9).

OBJECTIVES

The objectives of the present study are:

(a) to determine the effect of very low cooling rates (as experienced in the heavy sections of sand-cast propellers) together with the effect of alloy composition, especially Mn and Al contents, on fracture toughness,

(b) to determine the reasons for the dramatic reduction in impact properties of MAB propellers when compared with expected values, and

(c) to recommend industrially practicable heat treatments for improving impact resistance.

PRELIMINARY HEAT TREATMENTS

Charpy impact samples were machined from remnants of the CCGS John A. MacDonald's fractured blades, and given the heat treatments described in Table 4. Impact, magnetic and hardness properties were determined subsequently. The heat treatments (Table 4) are similar to those suggested by Raymond as Haines #1 and #2 respectively (6) except that Raymond cooled his specimens from 675 or 690°C to 315°C as quickly as possible followed by air cooling to room temperature.

The Haines #1 heat treatment may distort a propeller because of the high annealing temperature of 830°C.

As shown in Table 4, the impact properties following the Haines #2 heat treatment are insensitive to test temperature (20°C or -20°C), but strongly dependent on the cooling rate from 690°C. Although the test specimens were removed from heavy sections, water quenching from 690°C gave an impact strength of 34 J, whereas air cooling and cooling in vermiculite reduced the impact properties to 18 and 20 J respectively. A further decrease in cooling rate (55°C/h from 690 to 260°C) caused another significant drop in impact strength to about 12 J. Judging from the results of Table 4, there appears to be no relationship between impact properties and hardness.

Raymond (5,6) reported a link between high magnetic permeability and low impact strengths. Following Raymond's work, a Magne-Gage was used to measure the permeability of Charpy impact specimens [This instrument gives an artificial reading which can be converted to magnetic permeability as shown in Fig. 1] and the results are included in Table 4. It is evident that these limited test results do not indicate any definite relationship between magnetic permeability and CVN impact properties.

Frost and Raymond (10) proposed heating to 860°C, cooling to 675°C in 30 min, quenching in a salt bath, holding for up to 4 h at 480, 370 or 260°C and quenching in water. With these heat treatments, impact strengths of 30, 24 and 19 J respectively were obtained. There are two major objections to the proposed heat treatment(s):

(a) An annealing temperature of 860°C is called for, notwithstanding the risk of distortion at a temperature of 830°C noted by Raymond (6).

(b) The treatment also calls for rapid cooling (30 min) from the annealing temperature (860°C) to 675°C, quenching in a salt bath, and then quenching again in cold water from the aging temperature. Even if quenching can be accomplished without cracking, the rapid cooling that is essential cannot be achieved in heavy sections. Thus, although this treatment may improve the impact resistance of small specimens (1 x 1 cm), it may not necessarily be successful with very large castings.

At present, it seems the only hope of rendering large castings less brittle is to hold them at a moderate temperature - in the range of maybe 300 to 600°C - for a number of hours sufficient to prevent precipitation at lower temperatures.

As a first step to developing a heat treatment to restore the impact resistance of propellers - at least partially - a large number of tests were carried out on small specimens from MAB propeller blades. Ninety-six specimens were tested in total. Half the specimens were heated at 690°C for 5 h and quenched in water. These samples, and an equal number of specimens in the "as received" condition, were heated at 600, 550, 500, 450, 400 and 300°C for 1, 6, 24 and 72 h and quenched in water or air-cooled. The hardness and magnetic permeability of all the samples were determined and their corresponding microstructures photographed. This is now being evaluated for possible correlations and the intended use of the SEM might be very helpful in this respect.

LARGE CASTINGS

To provide the stock for further investigation and, in particular, to clarify the effect of manganese on properties, MAB alloys with 8, 10, 12 and 14% Mn, together with NAB (C95800) alloy for comparison, were cast in modified keel blocks (11) (for separately cast test bars) and in 356 X 203 X 127 mm blocks. The latter were soundest when cast on end on a 13 mm steel plate, the

upper part of the block acting as a riser for the lower part. The top of the casting was covered with an exothermic compound immediately after pouring.

Thermocouples were inserted in the centre of the keel block legs, and in the center of the large blocks at a distance of 150 to 225 mm from the chill, in order to determine the cooling rates. These results are compared with the rates of cooling in large propeller castings in Table 5.

A typical ice-breaker propeller (5.5 m diam, 4-blades, integrally cast) for the Canadian Coast Guard Service weighs about 13,000 kg in the finished condition. To produce this, approximately 23,000 kg of metal are poured into the mould to cast this propeller in NAB or MAB alloy. Similarly, about 7300 kg of metal are poured to cast a single blade weighing about 4500 kg in the finished condition. The blade tip may be about 25 mm thick whereas the hub section is about 600-900 mm in diam in such propellers. A casting of this size cools at a very slow rate.

To obtain a measure of the cooling rates, temperature measurements were carried out on cast propellers with the cooperation of Canadian Stone Marine Ltd., Iberville, Quebec. A single blade NAB propeller and two four-blade MAB propellers were tested. Thermocouples were inserted into the riser heads, approximately 20 mm from the hub of the propeller and into special blocks attached to the blade edges. The cooling rate results are given in Table 5. Typical cooling curves are shown in Fig. 2 for a MAB propeller.

These results clearly indicate that the cooling rate of the thinnest parts of a large propeller is considerably less (by a factor of 15 to 20) than that of the 356 X 203 X 127 mm block. The most striking discovery is the extremely low cooling rate of the blades (0.04°C/min) through the assumed critical temperature range (600-300°C and perhaps even lower) when compared with the 356 X 203 X 127 mm block (0.8°C/min) and even compared with the propeller riser (0.07°C/min). Although the blade freezes much sooner than the riser (2 h compared with 18 h), the huge heat reservoir of the riser reduces appreciably the cooling rate of the blades through the critical temperature range.

Cooling rate results were essentially identical for both NAB and MAB alloys.

Typical MAB microstructures obtained from separately cast test bars (modified keel blocks), from a large casting (356 X 203 X 127 mm) and from a representative propeller blade (150 mm section) are given in Fig. 3 to 5.

Tensile and impact test bars were machined from keel blocks and from large blocks, and average results are given in Table 6. The table also indicates the relative decrease of properties in the large block compared with those of the keel block. In cases where the property is higher in the large block, the figure appearing on the "loss" line is preceeded by a (+) sign.

It is seen that the reduction in tensile strength, yield strength and hardness is generally less than 10%; however, the elongation results are more inconsistent varying from a 33% reduction to a 27% increase. The impact strength of the large blocks is 12 to 31% lower than that of the keel blocks. The specific gravity of the alloys is normal, indicating that the amount of porosity in the large blocks is very small. The magnetic permeability of the large blocks is considerably higher than that of the keel blocks, especially in the 8 and 10% Mn alloys, but it is too early to assess the significance of this phenomenon.

CONCAST RODS AND BARS

In order to obtain the large number of test bars necessary for heat treatment experiments, 22 mm diam rods and 16 mm square bars of the four MAB alloys at two aluminum levels for each manganese level were produced by the continuous casting process (concast). Concast bars and rods of NAB at two aluminum levels were also produced for comparison. Tensile test bars will be machined from the rods and Charpy impact bars from the square bars.

Tables 7 and 8 give the properties obtained from concast rods and bars in the as-cast condition. Properties of sand cast bars of similar compositions are included for comparison.

There is no specification for concast MAB alloys in ASTM B505 as yet. However, Table 7 shows that all the concast compositions exceeded the minimum mechanical property requirements for sand-cast MAB alloys (ASTM B148-78 for alloy C95700) except alloys 2T and 6T where the elongation requirements were not met.

It is evident from Tables 7 and 8 that aluminum has the predominant influence on the mechanical properties. Because manganese also appears to have an appreciable effect on the mechanical properties, the properties of the concast MAB alloys were plotted against the "equivalent aluminum content" suggested by Edwards and Whittaker (12) for sand-cast MAB alloys. These are:

UTS vs. Al + Mn/6% (Fig. 6)

YS vs. Al + Mn/4% (Fig. 7)

El% vs. Al + Mn/8% (Fig. 8)

CVN impact vs. Al + Mn/8% (Fig. 9)

Numerical values of the "equivalent aluminum content" for the various alloys are given in Tables 7 and 8.

It may be noted from Tables 7 and 8 and Fig. 9 that similar impact properties can be obtained from concast rods and square bars of similar compositions.

However, Langham and Webb (1) found that mechanical properties could be plotted against Al + Mn/6% as has been done in Fig. 10. This figure demonstrates that, within experimental error, changes in properties as a function of composition can be adequately represented by the single relationship Al + Mn/6%, instead of several.

Mechanical properties of concast NAB alloys are known to vary only as a function of the aluminum content. The properties shown at the bottom of Tables 7 and 8 are in agreement with those reported earlier (13). Impact properties of alloys 2T and C1 and C2 are markedly lower than those of other alloys despite the fact that alloy 2T exhibited 19% elongation. Examination of the impact fracture surface of alloy C2 by SEM, showed intergranular fracture Fig. 11(a). The impact energy of C_2 was 9 J. The fracture surface of C_2 showed extremely small dimples when compared with C_3 at high magnification [Fig. 11(b,c)].

Microstructural examination in the optical and scanning electron microscopes revealed very fine martensitic structures in all the concast MAB alloys (Fig. 12 to 15). Optical micrographs [Fig. 12(a), 13(a), 14(a) and 15(a)] show a gradual decrease in the volume fraction of the β phase (dark etching) with decrease in Mn content. The propeller-shaped Fe-rich particles shown in Fig. 12(a) and 13(a) were not observed in the 10 and 8% Mn alloys Fig. 14(a) and 15(a). Scanning electron microscopy revealed fine elongated particles in the β phase, the volume fraction of the β phase decreasing with increasing Mn content. The composition of the fine phases has not yet been established. The micrographs show that the β phase did not break down to give a eutectoid structure even at 8% Mn as in NAB alloys (13). Thin foil transmission electron microscopy of these concast alloys will be carried out to examine other microstructural features.

It has been found recently that concast MAB rods (four months old) contained numerous cracks of various widths, mainly at lap marks (Fig. 16). Sections through these cracks showed them to be as deep as 1 mm, and with

blunt tips. The microstructure near the tip of the cracks seems to contain more and larger alpha particles than the general structure (Fig. 17). It is possible that cracking took place at high temperature during cooling, but because the rods were not examined immediately after casting, it is not possible to be certain. Further rods will be cast and, in the event that cracking is found to occur following casting, the rods will be stress relieved.

A crack count of the concast MAB rods was made and is reported in Table 9. It does not appear from this table that the cracking tendency can be directly related to the chemical composition of the rods.

Square MAB bars and NAB rods and bars cast two months ago, do not show any sign of cracks.

It may be noted that cracking of concast MAB alloys has been observed by Ampco Metals in Milwaukee. Prior to any thermomechanical processing for producing welding filler wires, the concast rods are machined to remove the cracks and then stress-relieved.

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Table 1. Chemical composition of MAB alloys.

Elements, %	ASTM/ANSI B148-78 C95700		British standards 1400:1973 CMAI	
	Min.	Max.	Min.	Max.
Copper	71.0	-	-	-
Tin	-	-	-	1.0
Lead	-	0.03	-	0.05
Zinc	-	-	-	0.50
Iron	2.0	4.0	2.0	4.0
Nickel	1.5	3.0	1.5	4.5
Aluminum	7.0	8.5	7.5	8.5
Manganese	11.0	14.0	11.0	15.0
Silicon	-	0.10	-	0.15

Table 2. Specified and typical mechanical properties.

Property	ASTM/ANSI B148-78	B.S. 1400:1973	Stone's typical values 12%MAB	14%MAB
Tensile strength, MPa	620	650	650-710	690-760
0.1% Proof stress*, MPa	275	280	275-325	310-385
Elongation, %**	20	18	20-35	20-35
Hardness, Brinell	-	-	160-210	170-210
Charpy impact strength, J	-	-	27-47	27-47

* The figure given under ASTM/ANSI designation is the stress producing an elongation of 0.5% under load and that under British Standards is 0.2% proof stress.

** The length on which the elongation is measured is 50mm (4D) in ASTM/ANSI designation, $5.65\sqrt{\text{area}} = 5D$ in British Standards and $4\sqrt{\text{area}}$ in Stone's typical values.

Table 3. Mechanical property results from propeller blades

Property	Raymond's average of 2 failed blades(1)	PMRL (1)					75% of spec. strength
		J.A. MacDonald			Franklin		
		Failed(2) (15-75mm)	Good blades (75mm) A	Good blades (75mm) B	Failed #1 (50 mm)	Failed #3 (150 mm)	
Ultimate strength, MPa	455	610	552	592	592	523	465
0.5% Yield strength, MPa	255	305	361	337	287	253	205
Elongation, % in 4D	10	18	12	19	14	13	-
Hardness, Brinell	140	160(3)	170(3)	170(3)	170(3)	170(3)	-
Impact strength, J	7-11	7.5	10.5	15	9	8	-

(1) PMRL results were obtained from blades containing at least 14% Mn and Raymond's 12% Mn.

(2) These results were obtained on substandard test bars.

(3) Results were converted to Brinell from Rockwell "A" scale.

Table 4. Preliminary heat treatment results.

Sample No.	Heat treatment*	Test temp °C	CVN impact strength, J**	M.Gage reading	Hardness RA
39	H.T.#1 + water quenched	20	53	0	53
38, 41	" + air cooled	20	28	47	53
18	" + vermiculite cooled	20	30	59	55
17, 44	H.T.#2 + water quenched	20	34	0	54
28, 50	" + " "	-20	34	0	56
11, 13	" + air cooled	20	17	52	55
26, 30	" + " "	-20	18	52	55
5, 15	" + vermiculite cooled	20	21	60	56
36, 46	" + " "	-20	20	58	56
42	" + *** (below)	20	12	43	52

* H.T. #1 consists of heating the sample to 480°C at an optional rate, from 480 to 830°C at 55°C/h, keeping for 2 h at 830°C, cooling at 55°C/h to 675°C, and cooling as indicated in the Table. H.T. #2 is identical, except that the annealing temperature is 690°C for 4 h.

** 1 ft lb = 1.36 J

*** sample #42 was cooled at 55°C/h to 260°C, then air cooled.

Table 5. Cooling rates of various MAB castings (°C/min).

	Molten stage to 300°C	600-300°C*
Modified keel block	6.0	3.0
Large block	1.4	0.8
Propeller blade edge	0.09	0.04
Propeller riser	0.09	0.07

* The cooling rate between 600 and 300°C was determined because it is thought that the phenomenon responsible for the drastic loss of impact resistance takes place in that range of temperature, may be even lower.

Table 6. Mechanical properties of sand cast NAB and MAB castings.

Melt No. alloy		2197 2304 NAB (C95800)		2219 8% MAB	2258 10%MAB	2203 12% MAB	2216 14% MAB
UTS,	Keel block	599	592	648	685	685	700
MPa	Large block	515	532	589	668	630	650
	Loss, %	14	10	9	2	8	7
0.5%Y.S.,	Keel block	227	228	273	308	301	333
MPa	Large block	213	221	256	290	286	303
	Loss, %	6	3	6	6	5	9
Elongat.	Keel block	-	27	15	25	17.5	21.5
% in 4D	Large block	17	18	19	18	18.5	16
	Loss, %	-	33	+27	28	+ 6	25
Impact,	Keel block	34	29	24	24	23	23
J	Large block	24	26	20	16	19	20
	Loss, %	30	12	17	31	18	12
Hardness	Keel block	52	53	55.5	55	55	55
RA	Large block	45.5	52.5	50	53.5	51.5	51.5
	Loss, %	12	1	9	3	6	6
Specific	Keel block	7.642	7.648	7.452	7.402	7.414	7.378
gravity	Large block	7.629	7.637	7.447	7.401	7.405	7.382
	Loss, %	0.17	0.14	0.07	0.01	0.12	+0.05
Reduction	Keel block	-	23.5	13.5	-	16	-
area, %	Large block	-	18	-	21	-	-
	Loss, %	-	23	-	-	-	-
Mag. Gage	Keel block	6	6	5	12	28	47
reading	Large block	9	8	17	37	46	51
	Loss, %	+50	+33	+240	+210	+65	+9
Composition							
	Aluminum, %	8.82	8.94	8.20	8.42	8.03	8.07
	Manganese, %	0.93	0.96	8.25	9.96	12.16	13.56
	Nickel, %	4.58	4.46	2.05	2.08	2.43	1.95
	Iron, %	3.94	3.82	3.14	3.13	3.23	3.50

Table 7. Chemical compositions and properties of concast MAB and NAB rods and sand-cast MAB alloys.

Melt No.	Type of casting	Composition, wt %				UTS, MPa	0.5% Y.S., MPa	El, % in 4D	Red. ar., %	Hardness, RA	CVN impact energy, J	Specific gravity	Magne-gage reading	Equivalent aluminum content, %		
		Al	Mn	Ni	Fe									Al+Mn/6	Al+Mn/4	Al+Mn/8
2238	sand	7.85	7.79	2.11	3.18	579	236	44	41	46	49	7.546	3	9.15	9.80	8.82
7T	concast	8.57	7.26	2.03	3.21	747	411	28	35	56	29	7.502	3	9.78	10.38	9.48
8T	concast	9.06	7.20	2.01	3.20	787	425	23	28	58	20	7.444	3	10.26	10.86	9.96
2250	sand	8.50	9.56	1.92	2.83	660	296	32	-	53	28	7.456	9	10.09	10.89	9.69
5T	concast	8.25	9.64	1.96	2.93	766	432	25	31	57	23	7.462	3	9.86	10.66	9.45
6T	concast	8.83	9.57	2.04	2.82	785	432	18	24	59	17	7.426	3	10.42	11.22	10.02
2241	sand	7.58	11.9	2.06	3.31	594	260	42	44	48	50	7.497	6	9.56	10.55	9.07
3T	concast	7.68	11.3	2.07	3.32	732	419	34	49	55	36	7.474	10	9.56	10.50	9.08
4T	concast	8.20	11.1	1.98	3.32	787	455	28	43	59	25	7.434	12	10.03	10.96	9.58
2242	sand	7.38	14.1	2.01	2.96	658	303	30	-	52	30	7.424	50	9.73	10.90	9.14
1T	concast	7.77	13.6	1.92	3.07	802	460	26	39	59	17	7.390	42	10.04	11.17	9.47
2T	concast	8.50	13.4	1.99	2.96	865	485	19	30	61	9	7.339	37	10.73	11.85	10.17
CA 20-1	concast	8.56	1.32	4.61	4.10	600	280	36	-	-	-	7.705	-	-	-	-
CA 20-2	concast	8.92	1.28	4.56	4.16	661	323	28	-	-	-	7.645	-	-	-	-

Table 8. Chemical compositions and properties of concast MAB and NAB square bars and sand-cast MAB alloys.

Melt no.	Type of casting	Composition, wt %				CVN impact energy, J	Hardness, RA	Specific gravity	Magne-gage reading	Equivalent aluminum content, %	
		Al	Mn	Ni	Fe					Al+Mn/6	Al+Mn/8
2238	sand	7.85	7.79	2.11	3.18	49	46	7.546	3	9.15	8.82
C7	concast	8.73	8.09	2.02	3.03	32	58	7.484	1	10.08	9.74
C8	concast	9.14	7.99	1.97	3.09	18	60	7.409	3	10.47	10.14
2250	sand	8.50	9.56	1.92	2.83	28	53	7.456	9	10.09	9.69
C5	concast	8.17	10.42	1.84	2.81	28	59	7.448	5	9.91	9.47
C6	concast	8.66	10.38	1.88	2.81	14	60	7.392	3	10.39	9.96
2241	sand	7.58	11.93	2.06	3.31	50	48	7.497	6	9.56	9.07
C3	concast	8.00	12.02	1.94	3.26	33	58	7.453	13	10.03	9.53
C4	concast	8.22	11.90	1.92	3.25	22	60	7.396	16	10.20	9.71
2242	sand	7.38	14.12	2.01	2.96	30	52	7.424	50	9.73	9.14
C1	concast	8.81	13.64	1.84	3.03	11	62	7.342	43	11.08	10.51
C2	concast	8.42	14.03	1.85	2.87	9	63	7.306	42	10.78	10.19
CA19-1	concast	8.30	1.28	4.58	4.22	60	-	7.711	8	-	-
CA19-2	concast	8.90	1.18	4.54	4.19	55	-	7.642	5	-	-

Table 9. Crack frequency in concast MAB rods.

Melt No.	Average Mn, %	Average Al, %	Cast length, cm	Number of cracks	Frequency, crack/cm
7T	7.26	8.57	528	69	0.13
8T	7.20	9.06	404	8	0.02
5T	9.64	8.25	456	134	0.29
6T	9.57	8.83	429	157	0.37
3T	11.3	7.68	526	7	0.01
4T	11.1	8.20	516	116	0.22
1T	13.6	7.77	526	185	0.35
2T	13.4	8.50	434	39	0.09

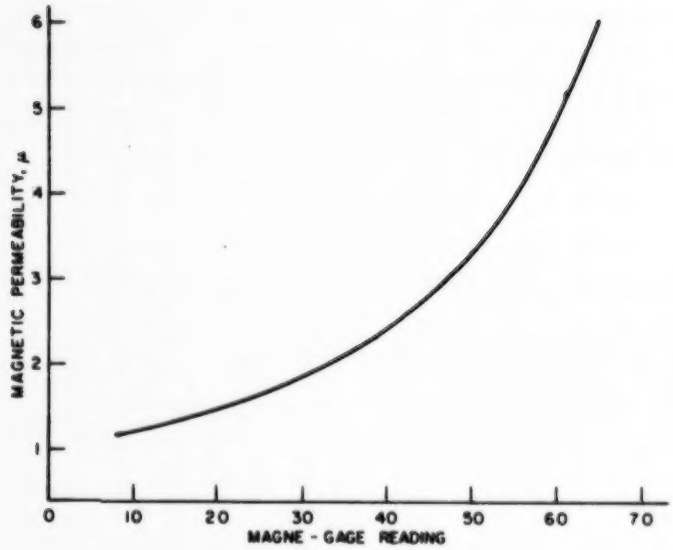


Fig. 1. Magnetic permeability vs. Magne-Gage reading. (neg 7003A)

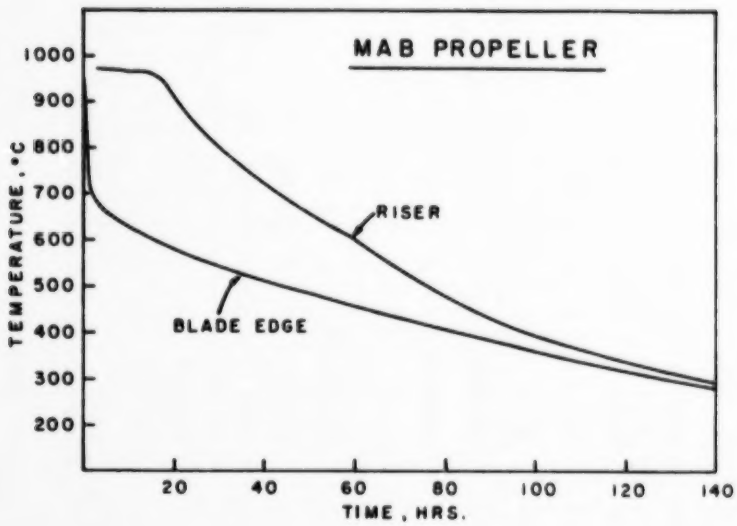
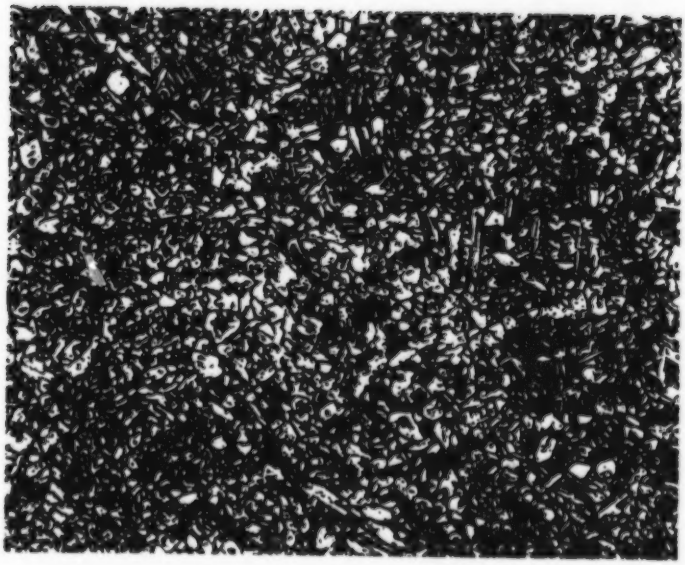
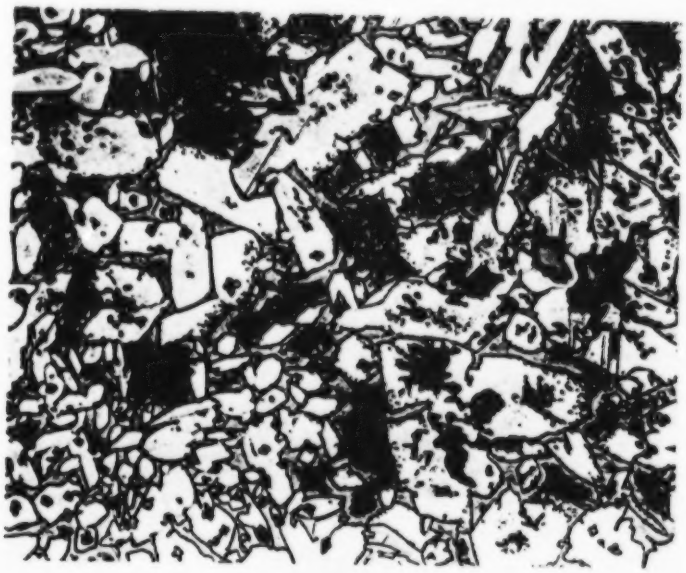


Fig. 2. Cooling curves obtained on a 13 000 kg MAB propeller. (neg. 6044).

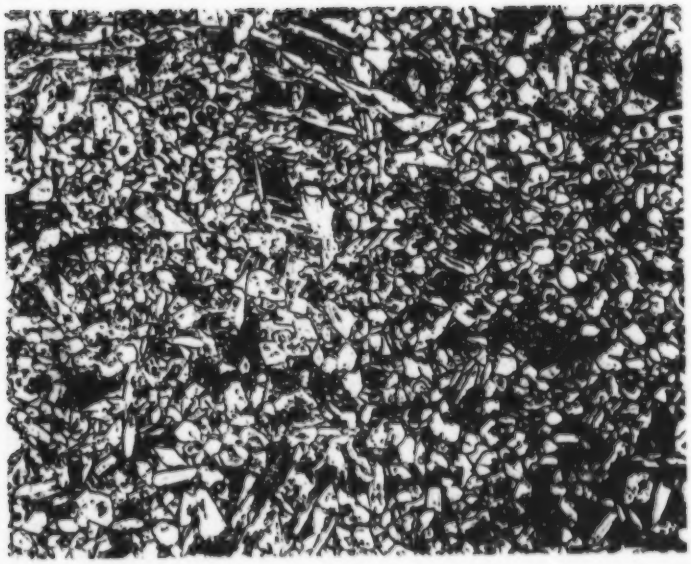


a) X100

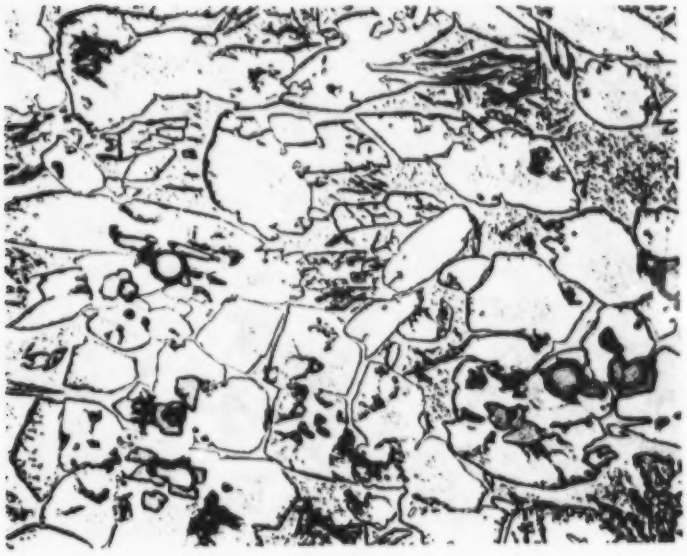


b) X500

Fig. 3. Microstructure of separately cast test bars
Cooling rate: 6.0°C/min. Melt #2216
13.56% Mn, 8.07% Al, 3.50% Fe, 1.95% Ni.
Etched in Alexander's reagent (neg. 7167 & 7164).

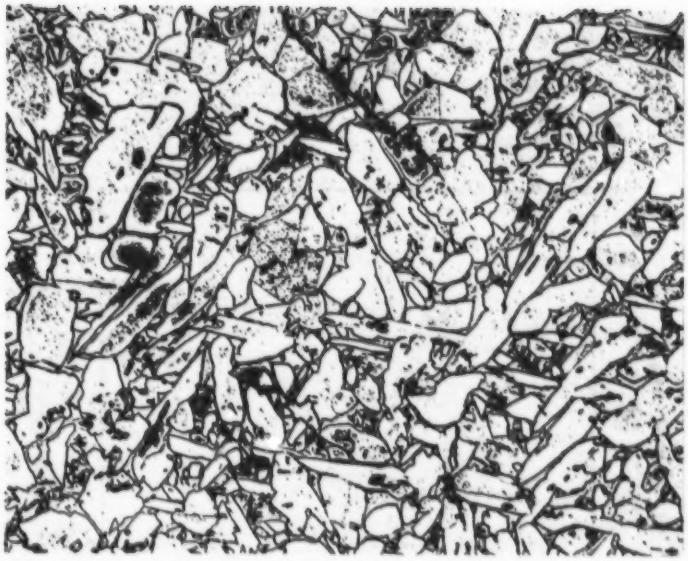


a) X100

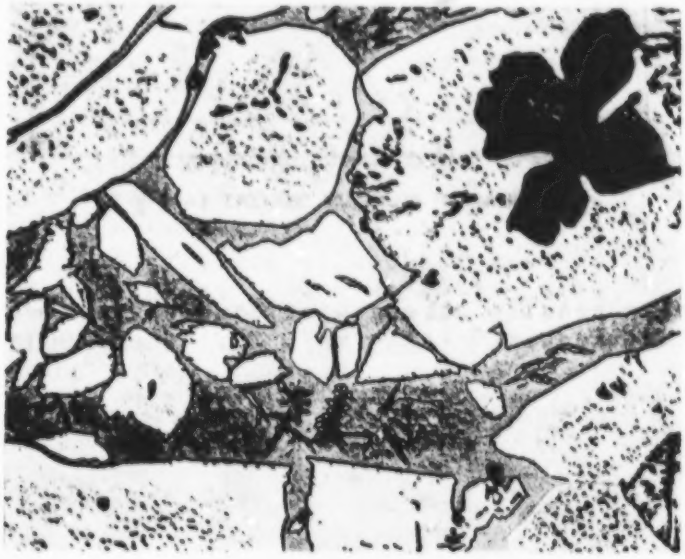


b) X500

Fig. 4. Microstructure of 356 X 203 X 127 mm block.
Cooling rate: 1.4°C/min. Melt #2216
13.56% Mn, 8.07% Al, 3.50% Fe, 1.95% Ni
Etched in Alexander's reagent (neg. 7165 & 7166)



a) X100



b) X500

Fig. 5. Microstructure of a propeller blade (150mm).
Cooling rate: 0.09°C/min.
14.68% Mn, 7.59% Al, 3.55% Fe, 2.14% Ni
Etched in Alexander's reagent (neg. 7168 & 7169)

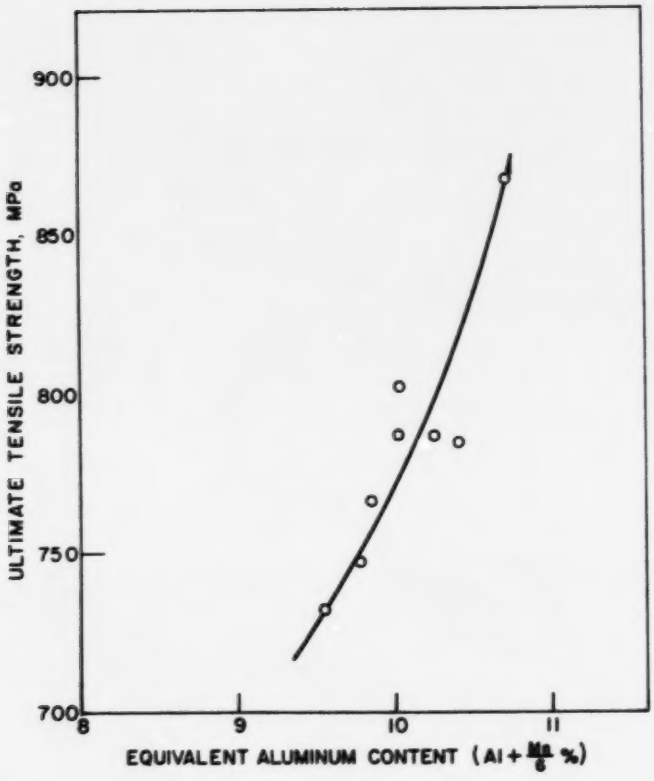


Fig. 6. Ultimate tensile strength of concast rods vs. "equivalent aluminum content" (Al + Mn/6 %). (neg 7003B)

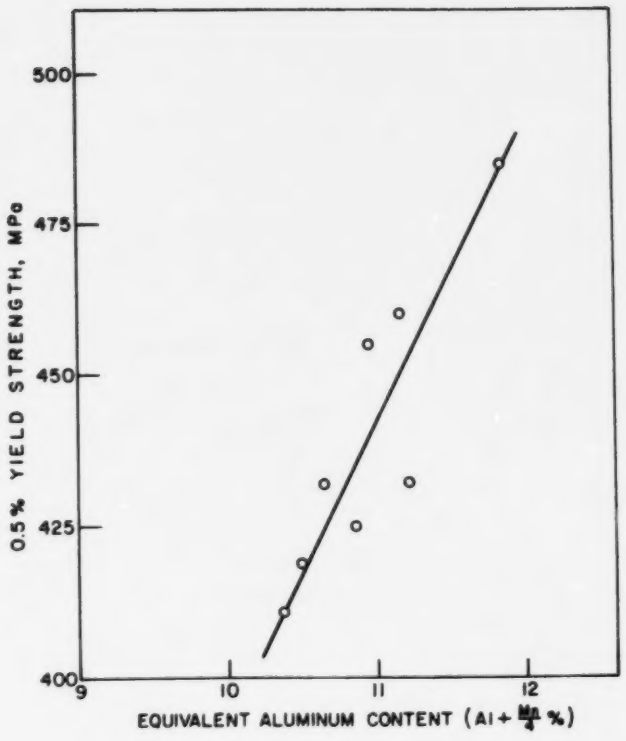


Fig. 7. 0.5% Yield strength of concast rods vs. "equivalent aluminum content" (Al + Mn/4 %). (neg 7003C)

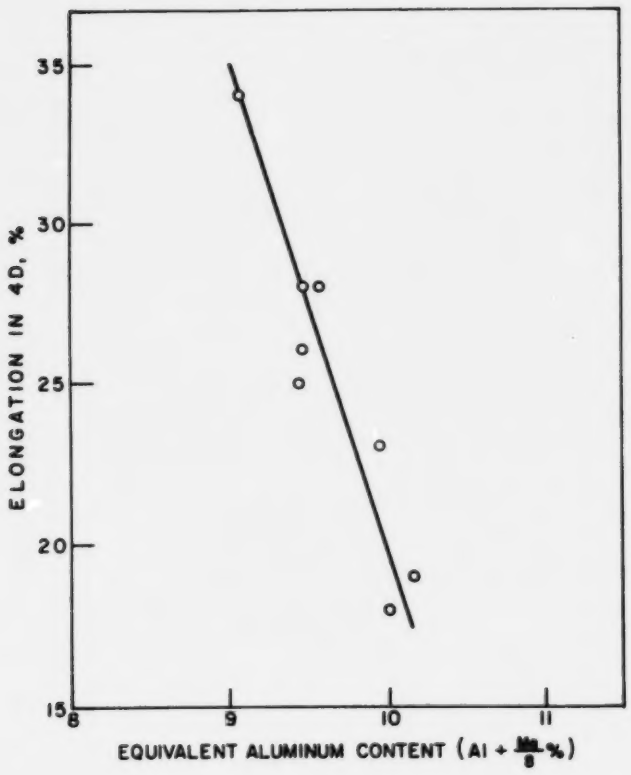


Fig. 8. Elongation of concast rods vs. "equivalent aluminum content" (Al + Mn/8 %). (neg 7003D)

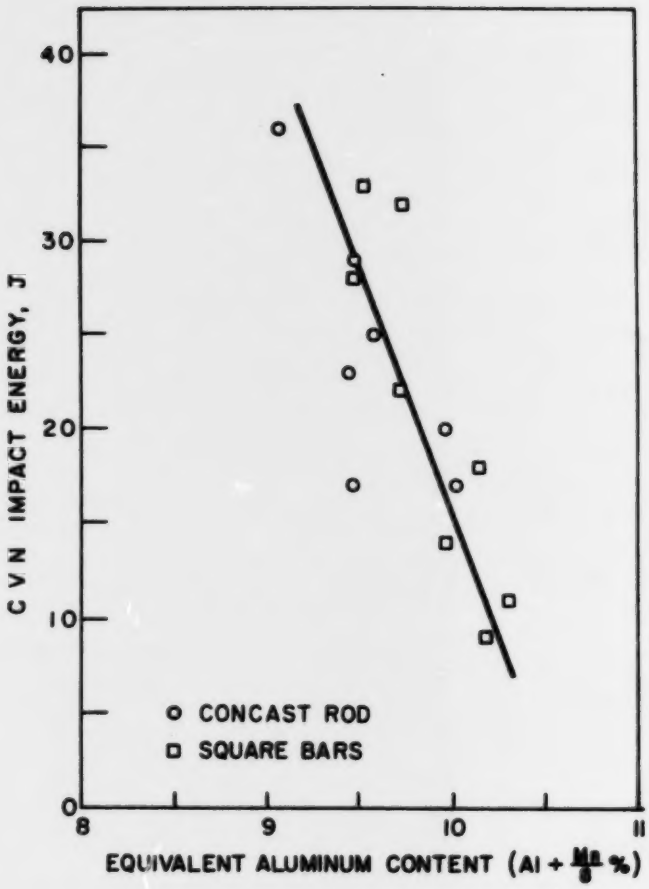


Fig. 9. Impact energy of concast rods and bars vs. "equivalent aluminum content" (Al + Mn/8 %). (neg 7003E)

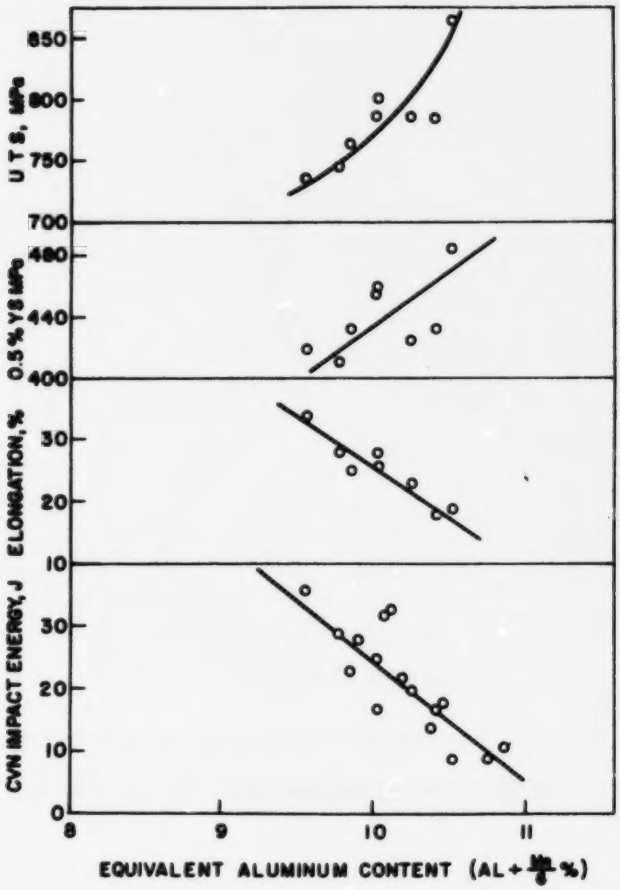
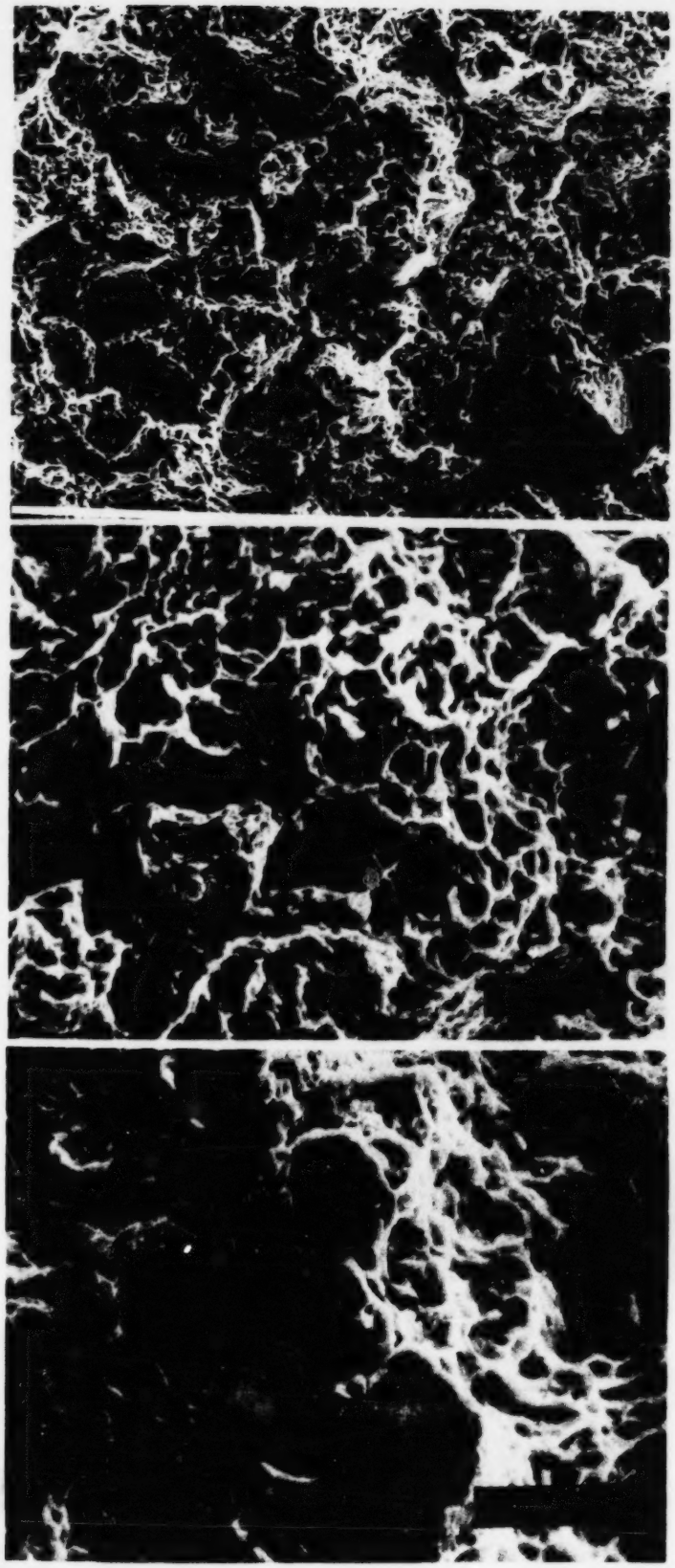


Fig. 10. Properties of concast rods and bars vs. "equivalent aluminum content" (Al + Mn/6 %). (neg 7003F)

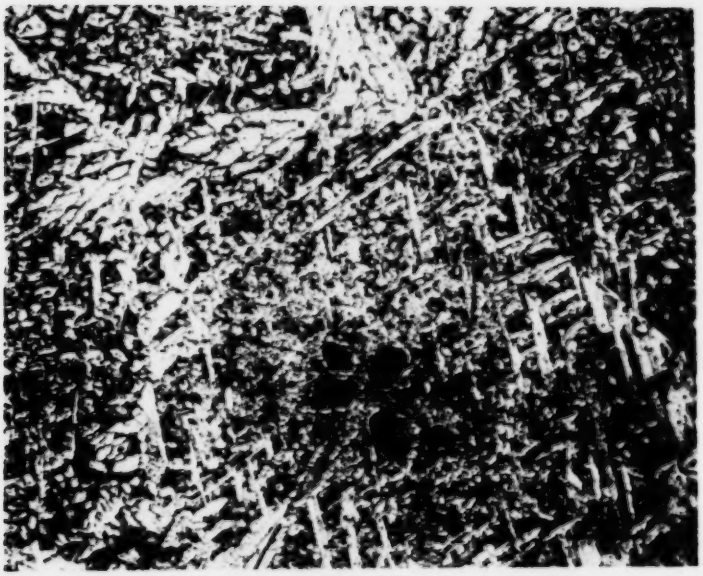


a) Alloy C2 14.03% Mn, 8.42% Al CVN impact value: 9J (neg 6142)

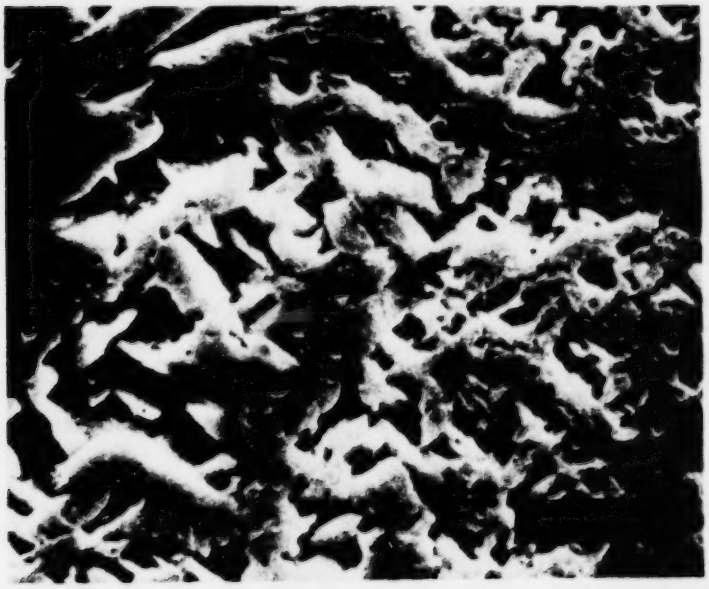
b) Same as above. (neg 6143)

c) Alloy C3 12.02R Mn, 8.00% Al CVN impact value: 33J (neg 6144)

Fig. 11. Scanning electron micrographs of concast MAB fractures impact specimens.

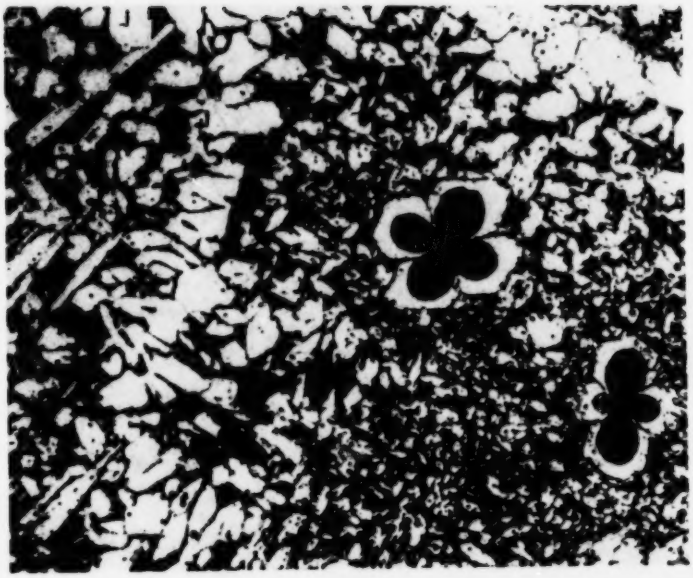


a) Optical X1000 (neg 6145)



b) SEM (neg 6146)

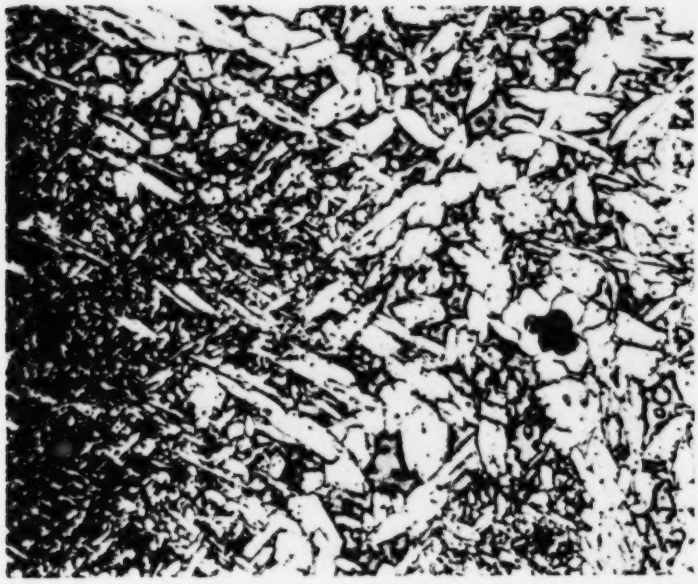
Fig. 12. Optical and scanning electron micrographs of concast rod 2T; 13.4% Mn, 9.50% Al. Alcoholic ferric etch.



a) Optical X1000 (neg 6147)

b) SEM (neg 6148)

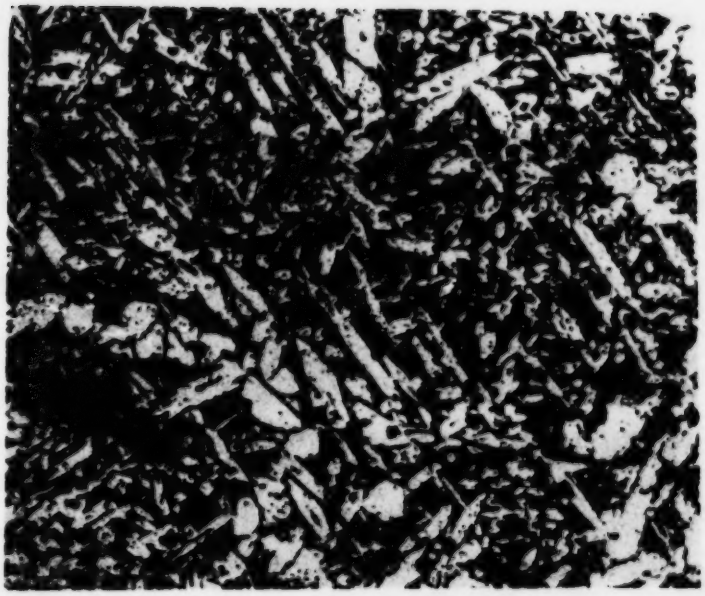
Fig. 13. Optical and scanning electron micrographs of concast rod 4T; 11.1% Mn, 8.2% Al. Alcoholic ferric chloride etch.



a) Optical X1000 (neg 6149)

b) SEM (neg 6150)

Fig. 14. Optical and scanning electron micrographs of concast rod 6T;9.57% Mn, 8.83% Al. Alcoholic ferric chloride etch.



a) Optical X1000 (neg 6151)

b) SEM (neg 6152)

Fig. 15. Optical and scanning electron micrographs of concast rod 8T; 7.2% Mn, 9.06% Al. Alcoholic ferric chloride etch.

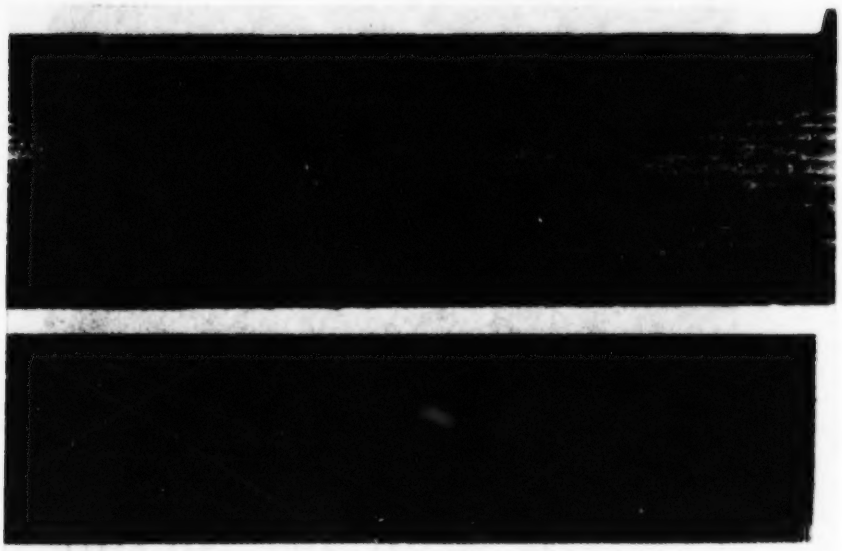
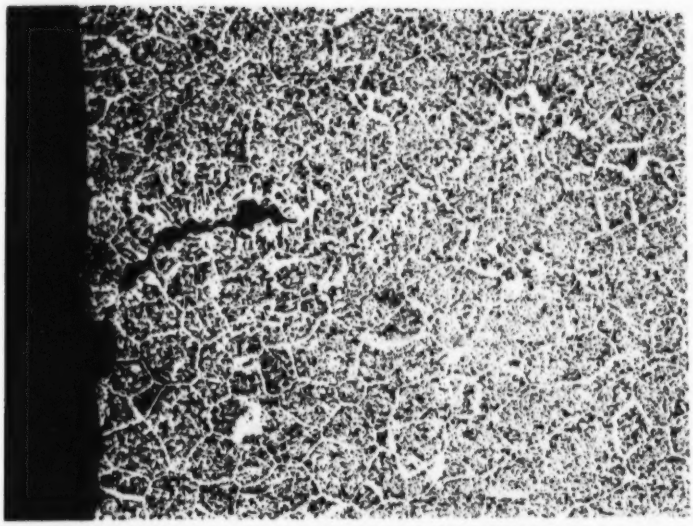
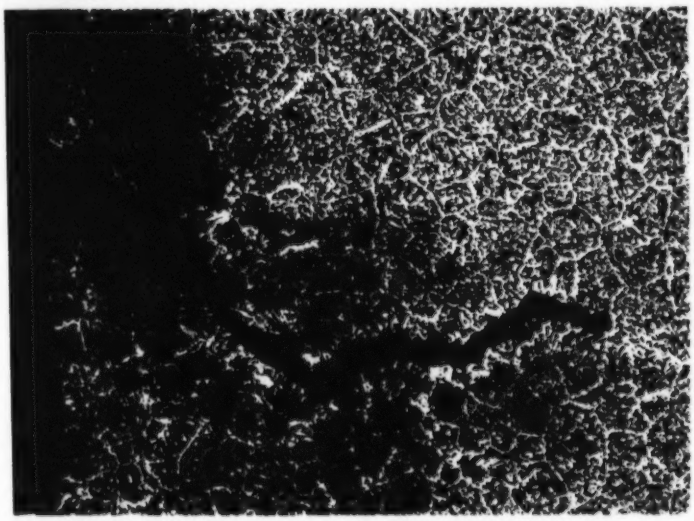


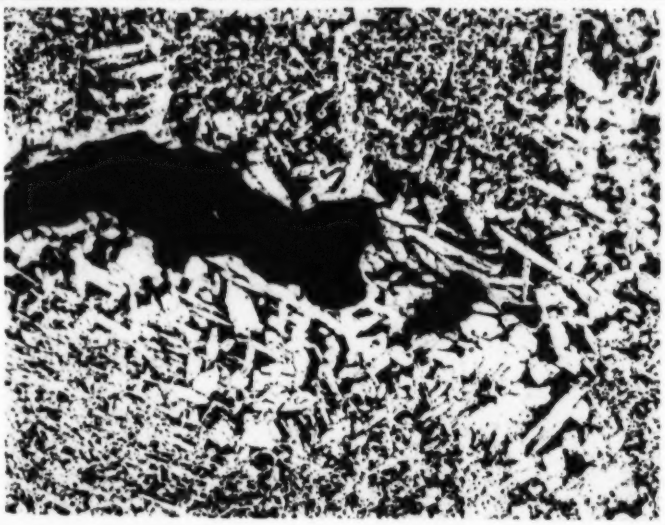
Fig. 16. Macrophotograph of concast rod 8T showing surface cracks 7.2% Mn, 9.06% Al. (neg. 6153)



a) X100 Surface crack
(neg 6154)



b) X100 Surface crack
(neg 6155)



c) X500 Crack tip
(neg 6156)

Fig. 17. Surface cracks in concast rod 8T; 7.2% Mn, 9.06% Al. Alcoholic ferric chloride etch.